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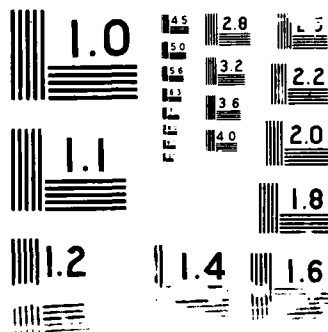
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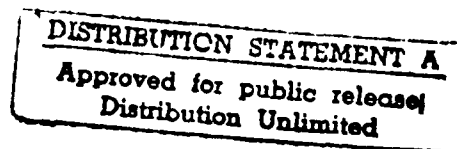
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MORE THAN A SOLAR CYCLE OF SYNOPTIC SOLAR AND CORONAL DATA: A VIDEO PRESENTATION

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Abstract

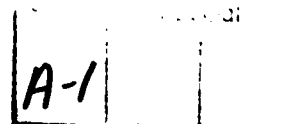
Color video movies of synoptic observations of the sun and corona can now be created. Individual analog frames on laser discs can be referenced digitally and played back at any speed. We have brought together photospheric magnetic field data from the Wilcox Solar Observatory at Stanford and the National Solar Observatory, model computations of the coronal magnetic field, and coronal data from the Sacramento Peak coronagraph and the Mauna Loa K-coronameter and made a series of movies presenting the data sets individually and in comparison with one another.

This paper presents a description of each of the data sets and movies developed thus far and briefly outlines some of the more interesting and obvious features observed when viewing the movies.

1. Introduction

Display of large amounts of data in a convenient and informative format is a more and more common problem. For example, a complete solar cycle of photospheric magnetic field data observed at the Wilcox Solar Observatory (WSO) at Stanford now exists. Examination of the entire data set for long term trends or slow evolutionary changes is difficult since the data are appropriately presented in frames showing one solar rotation. Further complications arise when one desires to compare a long interval of one kind of synoptic data with another.

Figure 1 shows thirteen Carrington rotations of WSO photospheric magnetic field measurements in the left column and the corresponding field at the source surface of a potential field model (PFM) in the right column. The PFM calculates the coronal field from the photospheric observations using the assumptions that the field becomes purely radial at a hypothetical source surface and that the field between the photosphere and source surface is a potential field. In our incarnation of the model, the source surface is a spherical surface located $2.5 R_{\odot}$ (solar radii) from the sun's center (Hoeksema et al., 1982, 1983). The photospheric data are shaded above a field value of 2 Gauss. PFM



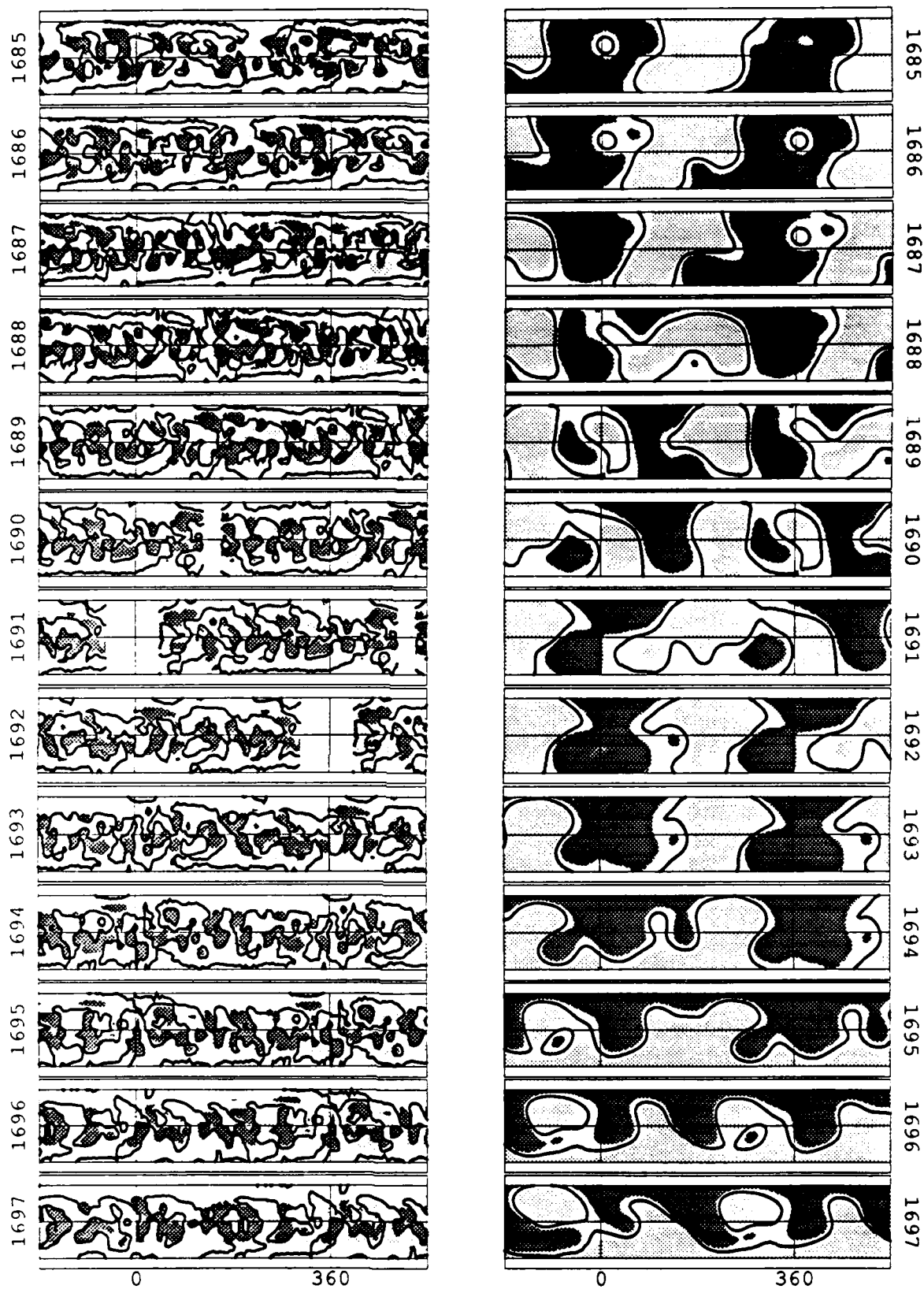


Figure 1: 13 Carrington Rotations of Photospheric and Source Surface Magnetic Fields from August 1979 to July 1980, the time around solar maximum.

values above 0.02 Gauss are shaded. Darker shading indicates negative field; lighter shading positive.

This interval includes the time of solar maximum and the reversal of the polar field. The source surface field is less ordered during this interval than during any other. This figure shows less than one year of data and only presents the neutral line and field polarity, yet comparison of the two data sets is difficult and much of the detail is obscured.

One solution to the problem is to make movies of the data. Recent developments in video equipment and laser disc storage make it an attractive medium for producing movies because of the ease of interface with computer generated graphics. Furthermore, a video system is a much more versatile tool for analyzing the data than a film projector. The movies described in this report have been prepared as part of a joint Stanford-Lockheed project and were recorded at the Lockheed Solar Group Image Laboratory. Images were processed on a VAX 11/780 using ANA, an interactive image analysis language. The individual frames were stored on laser disc by analog recording. The frames are referenced digitally and can be played at any speed in either direction.

We have gathered photospheric magnetic field data from WSO and the National Solar Observatory (NSO) and observed coronal intensity measurements from the Sacramento Peak Observatory (SPO) Coronagraph and the High Altitude Observatory (HAO) K-coronameter on Mauna Loa. We also have the magnetic field in the corona computed at the source surface using the PFM. Each of these synoptic data sets extends over most of Solar Cycle 21. The HAO observations extend back to 1965. The following movies have been produced so far.

1. WSO Photospheric Data and Computed PFM Source Surface Field
2. WSO and NSO Photospheric Data
3. Equatorial and Polar Projections of NSO Photospheric Data
4. Equatorial and Polar Projections of PFM Field
5. SPO Coronal Green Line Intensity at 1.15 and 1.35 R_{\odot}
6. SPO Coronal Brightness with WSO and PFM Neutral Lines
7. HAO Coronal Data at 1.5 R_{\odot}
8. HAO Data with WSO and PFM Neutral Lines Superposed
9. HAO and SPO Data with PFM Neutral Line Superposed

Each movie consists of a series of frames. Each frame presents data from about one Carrington rotation. Data observed each day (weather and equipment permitting) over an interval corresponding to the rotation period of the sun are used to build up a map of the entire solar surface. In the Carrington calendar, a given solar longitude is observed at central meridian each 27.27 days. The photospheric maps are generally presented in the Mercator projection and are called synoptic charts. In the movies the vertical scale is generally in equal steps of sine latitude because that more accurately reflects the resolution of the observed magnetic data. Time goes from right to left on synoptic charts, corresponding to the way the sun is observed to rotate in the sky. Boundaries of Carrington rotations are marked; generally a small area beyond each

edge of a rotation is shown for continuity.

Most movies show several interpolated images between each observed frame. We have developed an interpolation scheme that is smooth in time. Consider four consecutive observed frames: A, B, C, and D. To interpolate images between frames B and C, we first compute a quadratic fit, Q1, of frames A, B, and C and a fit, Q2, of B, C, and D. For time, t , in the range $[0,1]$ between frame B = F(0) and frame C = F(1), the interpolated frame is $F(t) = (1-t)Q1 + tQ2$. A number in the upper left corner of each frame indicates the interpolation number; in all movies frame 0 shows the observed data.

The photospheric observations, source surface data, and SPO measurements are interpolated onto 9 frames between each pair of observed frames. The HAO data are interpolated onto 4 frames between pairs of observed frames because there are two observed frames of HAO data for each Carrington rotation, one from the east limb and one from the west. In movies where coronal and photospheric observations are compared, no interpolated frames are produced.

2. The Movies

This section includes a brief description of each of the movies listed above and summarizes some of the more interesting features observed in each. The section numbers correspond to the movie number, e.g., Section 2.6 describes Movie 6.

2.1 WSO Photospheric Data and Computed PFM Source Surface Field

This movie presents data from June 1976 to June 1986 (Carrington Rotation (CR) 1642 to 1774). Each frame consists of two synoptic charts. The lower panel shows the WSO photospheric magnetic field. The resolution is 5 degrees in longitude by 30 steps in sine latitude. The thick black line indicates the zero level contour. Regions of positive polarity are blue and regions of negative polarity are red. This convention applies in all movies showing the magnetic field strength. The magnetic flux scaling varies by a factor of three during the solar cycle, as can be seen by the variations of the color bar on the side. Gaps in the data were linearly interpolated between two adjacent observed rotations. When the gaps are significant 'Missing Data' appears in the upper right corner.

The upper panel shows the source surface field computed by Hoeksema and Scherrer from the WSO data (Hoeksema & Scherrer, 1986) using the potential field model with the source surface radius at $2.5 R_{\odot}$. The maximum field strength at the source surface changes much less during the cycle, so the color scaling is constant. The source surface field is a model of the coronal field at the base of the solar wind. We assume that the solar wind carries this field pattern radially outward into the heliosphere. Thus the structure shown in these maps describes the structure of the heliospheric current sheet which separates regions of polarity in the interplanetary medium that point toward and away from the Sun.

The photospheric field is much more complex and variable than the source surface field. Photospheric field structures are not generally thought of as migrating across the equator, however, they are occasionally observed to do so in the movie, particularly in the later part of the solar cycle. Differential rotation is clearly visible in the photosphere, but is not nearly as strong at the source surface. A close inspection can reveal that the northern hemisphere source surface field rotates slightly faster than the southern field.

2.2 WSO and NSO Photospheric Data

Movie 2 includes data from January 1977 to July 1984 (CR 1650 to 1750). Again two panels of data are shown. The lower panel is the same as described above, showing the WSO photospheric field.

The upper frame represents the NSO photospheric field. The data are averaged from the original high resolution into bins that are one degree in longitude by $1/180$ of the north-south distance in equal steps of sine latitude. A white vertical bar on the right side shows the normalized total absolute flux in a single Carrington Rotation and gives an indication of when the image occurs in the solar cycle.

The nature of the structures changes very slowly. The lifetimes of the field patterns are often quite long. Another feature to notice is the somewhat surprising north-south motion of strong field regions, e.g. features cross the equator in CR 1687 at 200° and in CR 1706 near 0° . The field from the two observatories corresponds very well. Of course the NSO data shows features of higher resolution and measures more accurately the total flux present on the solar surface. However the WSO data shows the larger scale organization that is not readily apparent in the higher resolution data, since it is more sensitive to large-scale weak fields. This is particularly true near solar minimum. Easily visible in both data sets are patterns that originate at lower latitudes and later merge with higher latitude unipolar regions that are extended in longitude.

Note: The missing data in the NSO magnetograms were set to zero for interpolation purposes. This becomes apparent when large grey areas show up on NSO synoptic charts. Unfortunately, this also influences the absolute flux indicator as the contribution of missing data is zero.

2.3 Equatorial and Polar Projections of NSO Photospheric Data

This movie includes data from January 1977 to July 1984. As in the previous movie it presents NSO magnetic data; however, in this case a 26.9 day rotation period was assumed rather than the Carrington rate. This corresponds to the rotation period of the equator rather than the more magnetically active middle latitudes.

We have also added polar views to the display. The data have been projected onto two circular regions and correspond to the views of observers located over the Sun's

poles. Because of the discontinuity at the edges of the synoptic charts (which are observed about a month apart and have therefore evolved) there is a seam on each of the polar disks. The data were multiplied by a factor of $(1+\cos(\text{latitude}))$ to partially compensate for the geometrical projection factor. Data close to the poles should not be trusted because of the decreased latitude resolution and the large projection effects.

The large unipolar structures appear to originate at low latitudes in high field regions and eventually migrate to higher latitudes and extend over a large range in longitude. They look like plumes of smoke in the Mercator projections and like spirals in the polar projections.

Some of the structures cross the equator, particularly in the declining phase of the cycle. Many of the structures and centers of activity are very long-lived. Watching this movie at very high speeds is particularly revealing because of the effects of differential rotation. Because so many of the features live for long periods and because they often merge into the existing large scale magnetic pattern, the large scale patterns seem to move much more slowly than the individual elements of stronger flux that contribute to the pattern.

The polar views strikingly show how the flux is confined almost completely to the equatorial region. The progression of the field patterns observed near the reversal of the polar fields around the time of solar maximum is also fascinating.

2.4 Equatorial and Polar Projections of PFM Field

Movie 4 includes data covering nearly an entire solar cycle, from June 1976 to June 1986. It displays the field on the source surface as in Movie 1, except that polar views have been added and the data has been made continuous at Carrington rotation boundaries by imposing different conditions on the way the data set is constructed.

Dipole and quadrupole patterns dominate the magnetic structure. Most of the structure occurs near the equator, particularly near solar minimum. The form is simple through most of the cycle, there being 2 or 4 warps in the neutral line, warps that correspond to 2 or 4 polarity sectors in the interplanetary medium. Near solar maximum, when the polar fields are reversing, the configuration is more complex and multiple neutral lines occasionally occur. In spite of the complexity, the continuity of the structure from one rotation to the next is amazing. During most of the cycle the structure changes very little during a 6 month to 1 year interval.

The polar projection provides a different perspective on the polar field reversal. The fields seem to fade rapidly at both poles in 1979 and then build again in 1980, but with the opposite polarity. The equatorial projection shows a gradual motion of the polarity pattern away from one pole and toward the other. From one rotation to the next very little seems to change, but after 3 or 4 rotations the rearrangement is very great.

The fields in the northern and southern hemisphere appear to rotate at different rates. This is particularly obvious in the early part of the solar cycle when playing the movie at high speed.

2.5 SPO Coronal Green Line Intensity at 1.15 and 1.35 R_S

Including data from June 1975 to August 1986, this movie shows coronal green line observations from Sac Peak in synoptic form. Two heights of observations are displayed in different panels: 1.15 and 1.35 R_S . The resolution is 10 degrees in longitude by 3 degrees in latitude. The white dots outside the data frames indicate longitude bins which were initially empty because of missing data. Each bin was filled using the average of the east and west limb observations for that Carrington longitude. If one limb was missing, data from the other limb were used. Remaining gaps were eliminated using the following procedure:

- One and two bin gaps were filled by interpolating spatially between adjacent longitude bins.
- Empty bins were then filled by averaging data from the previous and following rotations when possible.
- Finally, the first step was repeated but only for one bin gaps.

The remaining missing bins have been left black.

Brighter colors show regions of higher intensity. The color bars on the left side of the synoptic maps are scaled in millionths of the intensity at the center of the solar disk. Changes in the scaling indicate a very large variation over the solar cycle of the total flux. The total brightness also changes significantly from rotation to rotation and seems to be highly concentrated at low latitudes over the activity zones. There are less intense structures at higher latitudes which are sometimes stable for many rotations.

2.6 SPO Coronal Brightness with WSO and PFM Neutral Lines

Movie 6 is just a succession of frames of observed data. Two panels showing the SPO 1.15 R_S data are displayed as in Movie 5, except that the zero contour of the WSO photospheric field and the neutral line of the PFM data have been superimposed on different panels. We display the 1.15 R_S intensity rather than the 1.35 R_S data to compare with both the photospheric and coronal magnetic field and because there are fewer missing observations.

The brightness low in the corona seems better correlated with the photospheric field than with the source surface field, particularly the structures at higher latitudes and in regions of emerging flux. The source surface field may give clues as to which part of the photospheric neutral line will be most active, but is not generally a good predictor of where the green line will be observed. The degree of variability in the green line corresponds better to the variations in photospheric activity than to the more gradual evolution of the computed coronal field. The location of coronal material corresponds closely to the neutral line *higher* in the corona, as observed by the HAO instrument. The PFM is computed at 2.5 R_S , whereas the $\lambda 5303$ intensity is observed very low in the corona (1.15 R_S) and consequently corresponds more closely to the field configuration of the photosphere. The green line coronal structures are sensitive to

temperature as well. The temperature structure is not related to the magnetic field in the same way as the density and activity affects the green line more directly.

2.7 HAO Coronal Data at 1.5 R_S

This movie shows coronal electron density measurements gathered with the K-coronameter on Mauna Loa. The observations were made at 1.5 solar radii. The resolution is one day (~13 degrees) by 5 degrees of latitude. The intensity is measured in units of $10^{-8} \text{ erg cm}^{-2} \text{ ster}^{-1}$. White dots above the Carrington chart indicate whether data has been interpolated, either by linear interpolation or by using the measurements from the opposite limb during the same Carrington rotation. Appearance of a vertical black stripe indicates no data for that particular day. Since measurements are taken on each limb, 4 frames are interpolated about each limb in forming the time sequence. The source of the data is indicated in the upper right corner.

This movie is in three parts:

- July 1965 to February 1968 (CR 1496 to 1530).
- May 1969 to August 1978 (CR 1548 to 1672).
- August 1980 to March 1984 (CR 1698 to 1747).

The HAO data span a very long time interval and this provides an opportunity for comparing multiple sunspot cycles of synoptic data. Instrumental improvements can be seen in more complete coverage, increased contrast, and improved stability. Even over this long period the similarities of the observations made at comparable times in the solar cycle are striking. Near solar minimum all of the coronal material is concentrated very near the solar equator. Just before and after maximum material is present at all latitudes and long-lived structures are difficult to discern. During the declining phase the location of maximum brightness is very stable. Even more stable than the regions of maximum brightness are the largest areas of low intensity. These regions, which correspond to the locations of high field strength on the source surface and to the locations of coronal holes, have the longest lifetimes and the slowest evolution. A curious feature that shows clearly in the movies is a slight wobble in the images introduced by a small change in the latitudes of features observed on the east and west limbs. This could be caused by a small error in the mapping of the sun's north pole in the final data set.

2.8 HAO Data with WSO and PFM Neutral Lines Superposed

This movie is similar to Movie 6. The PFM and photospheric field neutral lines are superimposed on panels displaying the Mauna Loa coronal observations. The interval covered is June 1976 to March 1984 (CR 1642 to 1746) with a gap from August

1978 to August 1980 (CR 1672 to 1698). The east and west limb observations are shown separately. For each limb, the magnetic field was computed by taking a weighted average ($\frac{3}{4} - \frac{1}{4}$) of the nearest (in time) and second nearest Carrington rotation.

The correlation between the source surface neutral line and the maximum brightness regions of the coronameter data is amazingly good. Even though the HAO data is observed at $1.5 R_S$ and the PFM computations apply at $2.5 R_S$, the structures in the two data sets match extremely well. The correspondence is weakest during solar maximum when the maximum brightness regions are difficult to localize and short lived features contribute the most to the coronal brightness. The potential field model is also least accurate when the fields are evolving rapidly, which is more often the case when the fields are strong near solar maximum. The correlation is best during the times of the most stable structure, i.e. during the declining phase of the cycle and at solar minimum.

2.9 HAO and SPO Data with PFM Neutral Line Superposed

Movie 9 displays both SPO and HAO coronal data. The PFM neutral line has been superimposed on both. The upper frame contains the Sac Peak data. The higher $1.35 R_S$ brightness is shown here for comparison with other coronal data at similar altitudes. The HAO data results from averaging the east and west limbs. The interval covered is June 1976 to March 1984 (CR 1642 to 1746) with a gap from August 1978 to August 1980 (CR 1672 to 1698).

This movie allows comparison of the coronal field at three different levels. SPO at $1.35 R_S$, HAO at $1.5 R_S$, and PFM at $2.5 R_S$. As mentioned in the discussion of Movies 6 and 8, the HAO and PFM agree very well, while the SPO data are more similar to the photospheric field, even at this higher altitude. Seeing both the SPO and HAO together and noticing the similarities and differences is interesting. The two are obviously related, but the HAO shows brightness enhancements in only a subset of the areas highlighted in the SPO. The differences must be due to the increased complexity of the coronal field structure at the lower altitudes (1.35 compared to $1.5 R_S$) and to the temperature sensitivity to local activity. The PFM is simpler than either of the two observed data sets, which is probably due in part to the necessary simplification of the physics in the model and partly to the higher altitude at which it is computed.

3. Conclusions

Video movies are an effective tool for presenting large amounts of synoptic solar and coronal data in an informative way. This medium assists the observer in recognizing patterns in structure and evolution of large scale features that would be almost impossible to see in any other way. The comparison of multiple data sets is another avenue of research that requires further work. Watching these movies not only familiarizes the observer with the changing nature of the solar and coronal phenomena and

points out to him features that would otherwise go unnoticed, it also suggests further quantitative studies that can lead to a deeper understanding of the physics of the phenomena being observed.

Videotape copies of these movies played at various speeds may be obtained from the authors.

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